NIKON CORPORATION
Lens Engineering Development Department
Core Technology Center

EUV scattering from Mo/Si multilayer coated Mirrors

Kazutami Misaki and Noriaki Kandaka
Nikon Corporation

E-mail: Misaki.Kazutami@nikonoa.net

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Abstract

Mo/Si multilayer coated mirrors are employed in EUVL as main optical element. Scattering due to surface and interface imperfections crucially affects the throughput and image contrast of EUV optics. Unlike the scattering from a single surface, scattering from multilayer mirrors is very complicated. Specifically, we have to consider the effect of interfere between each layer (i.e., optical path difference of the scattered light). We have performed measurements of EUV scattering from Mo/Si multilayer mirrors with various conditions: substrates, coatings, wavelengths, and configurations. In particular, we measured the angle-resolved scattering not only in the “reflecting plane” which includes incident and reflected beam, but also in the direction perpendicular to the “reflecting plane”. As a result, they were distinctly different. In other words, 2-dimensional scattering distribution was examined and found to be anisotropic around the specular peak, as expected by the effect of multilayer interfere. As approaching normal incidence this discrepancy should be small, however, it is not negligible even at the incident angle of 10 degree. EUV reflectivity and the surface power spectral density are also examined in conjunction with the scattering distribution. The relationship of these properties and the performance of Mo/Si mirrors are discussed in detail.

Scattering from a single surface

Born approximation for scattering from a single surface

$$\frac{1}{I_0}\frac{dI}{d\Omega}=\frac{16\pi^2}{\lambda^4}R\cdot PSD(f) \qquad \cdots(1)$$

λ: wavelength

R: Reflectivity

I_0: incident Intensity

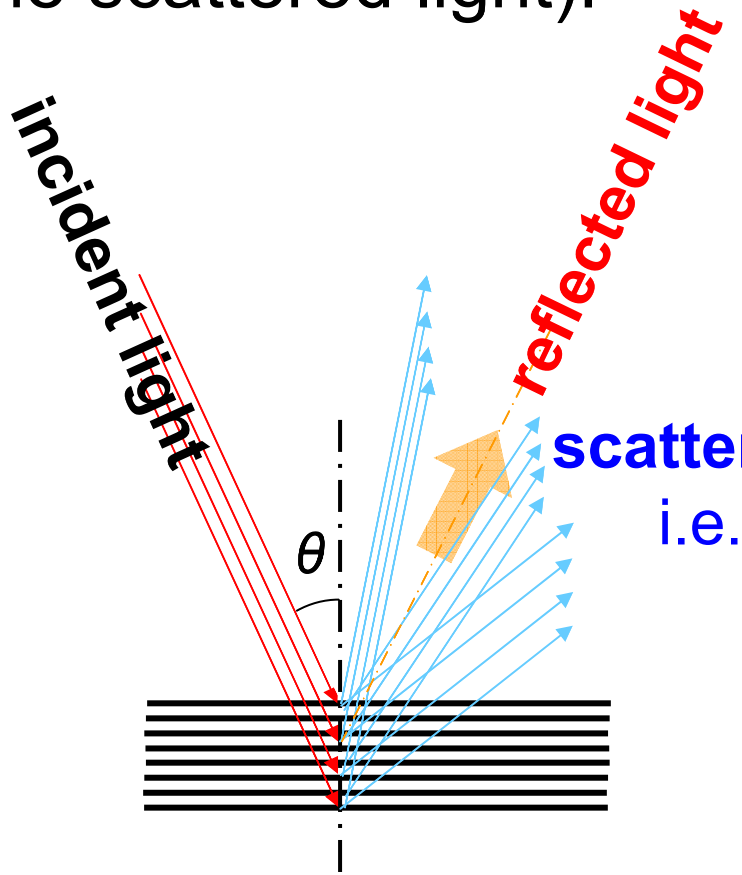
PSD: Power Spectral Density of a surface

agrees with the measured tail in the case of small roughness, near normal incidence and small scattering angle.

E. Gullikson, Proc. SPIE 3331, pp. 72-80

Scattering from multilayer

We have to take into account the effect of interfere between each layer (i.e., optical path difference of the scattered light).



scattered light : every direction

i.e., various state (phase shift)…

phase coherent ⇒ high scatter

phase lag increase ⇒ attenuated

N. Kandaka, et al., EUVL symposium 2004

Measured samples

4 samples with different level of smoothness:

rough

sample A

sample B

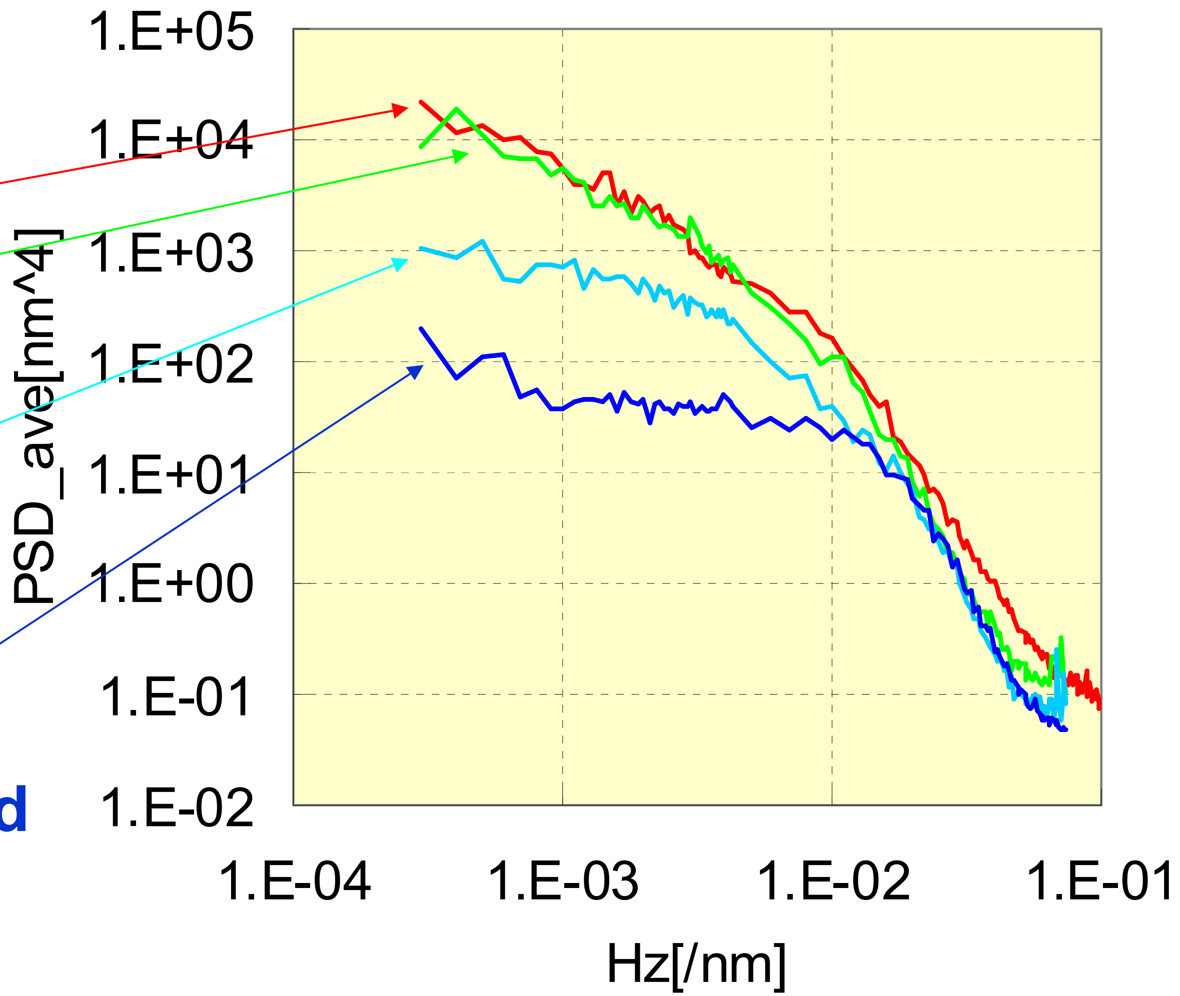
mid-level

sample C

smooth

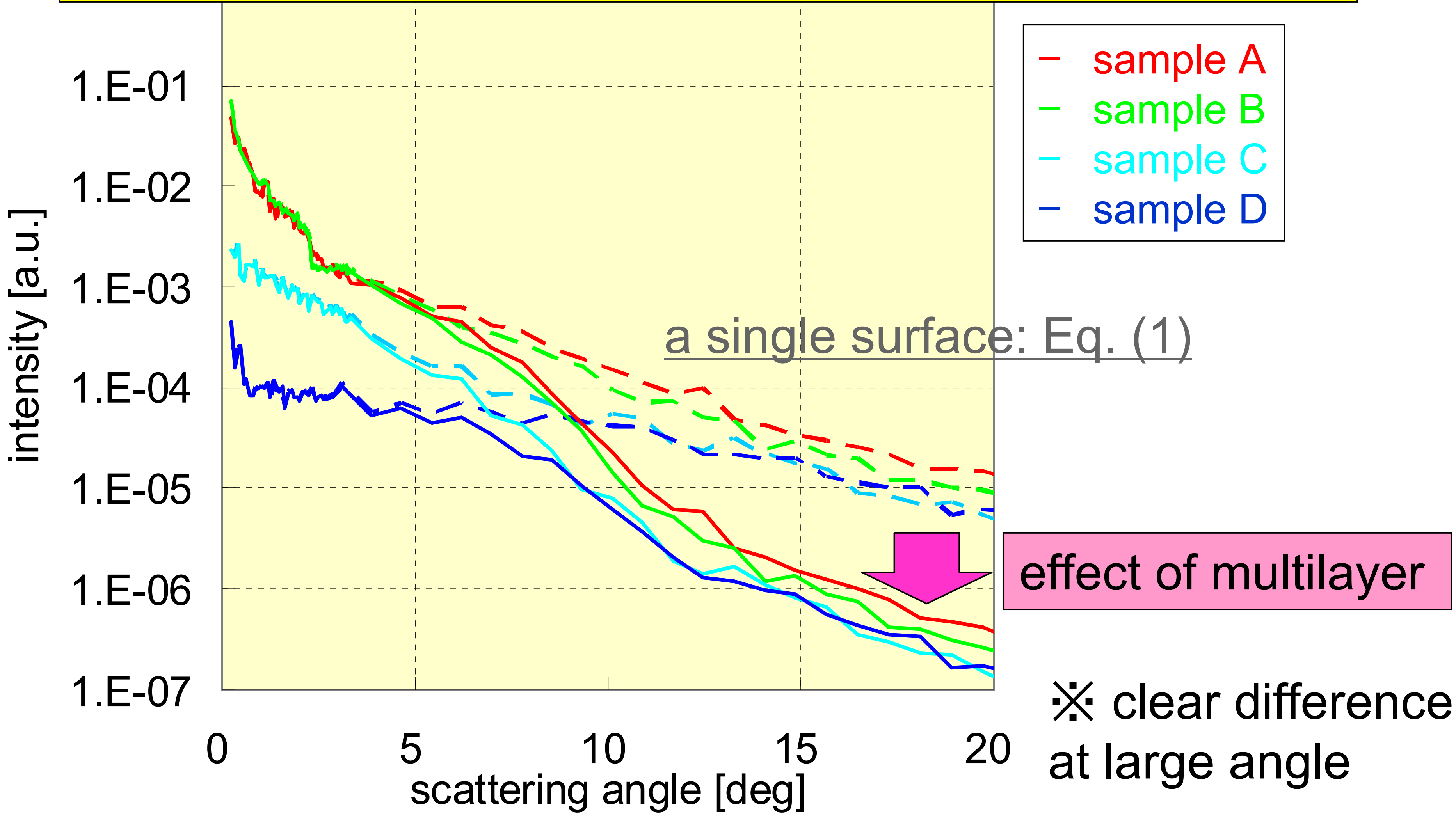
sample D (ML deposited on Si-wafer)

PSD after ML depo. measured by AFM (in house)



Effect of interfere between each layer

Scattering tail deduced (calculated) from PSDs



※ clear difference at large angle

Measurement facility: PF (KEK) BL-12A

KEK Photon Factory (PF)

Synchrotron facility : BL-12A

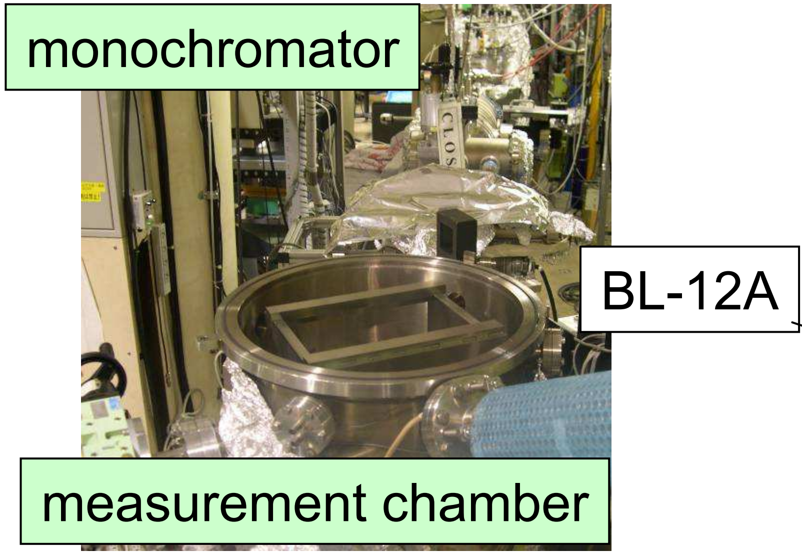
- ✓ strong intensity

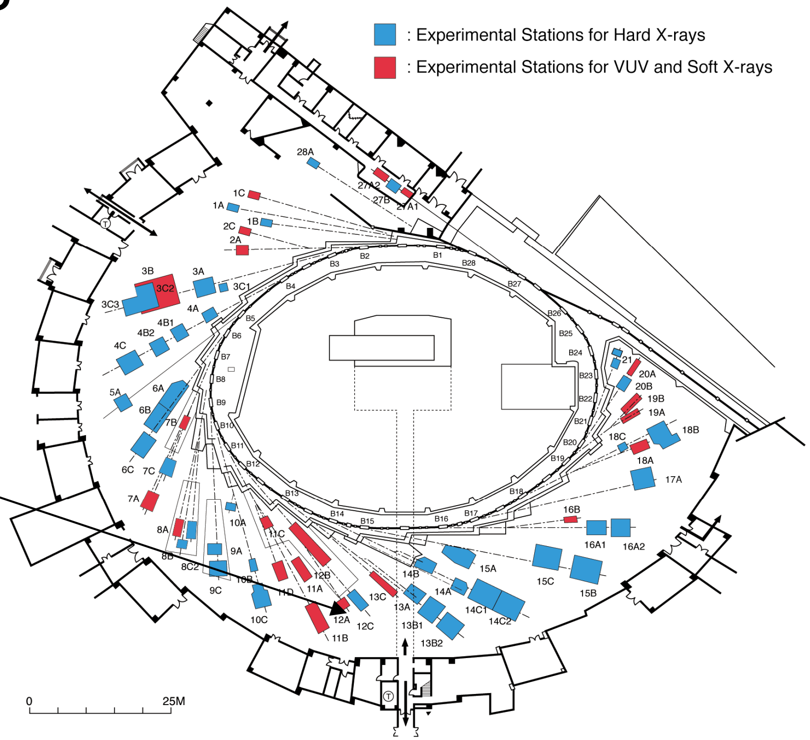
Detector with variable applied voltage

- ✓ dynamic range: 6 order of magnitude

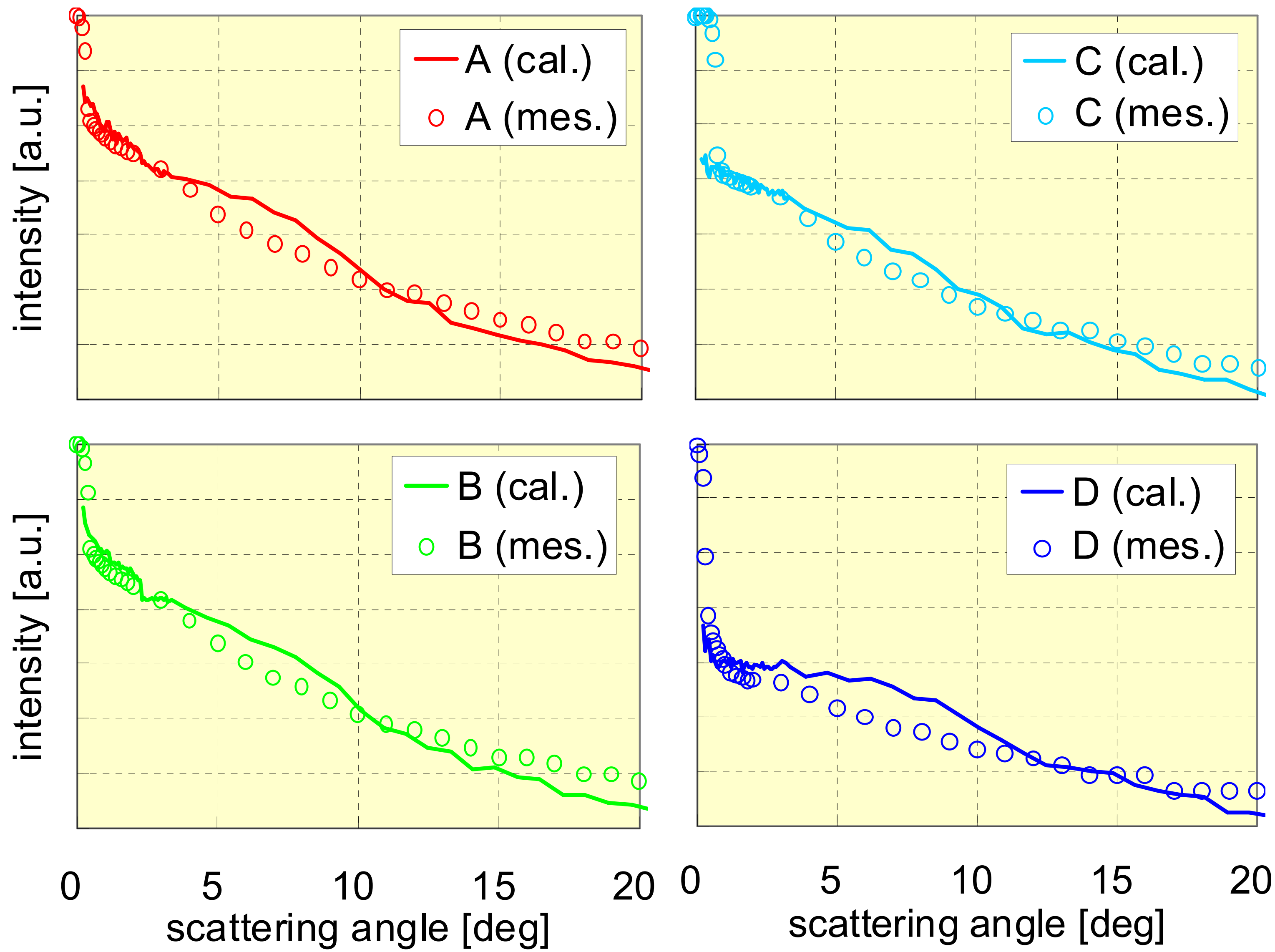
suitable to study scattering

Courtesy of KEK





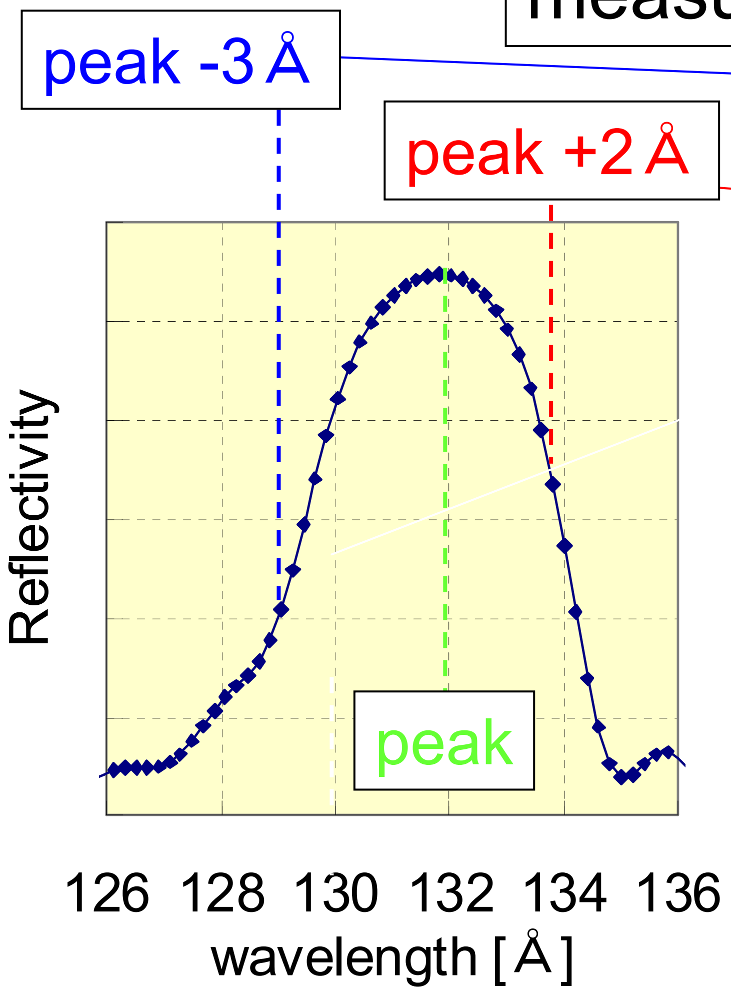
Measurements and calculations

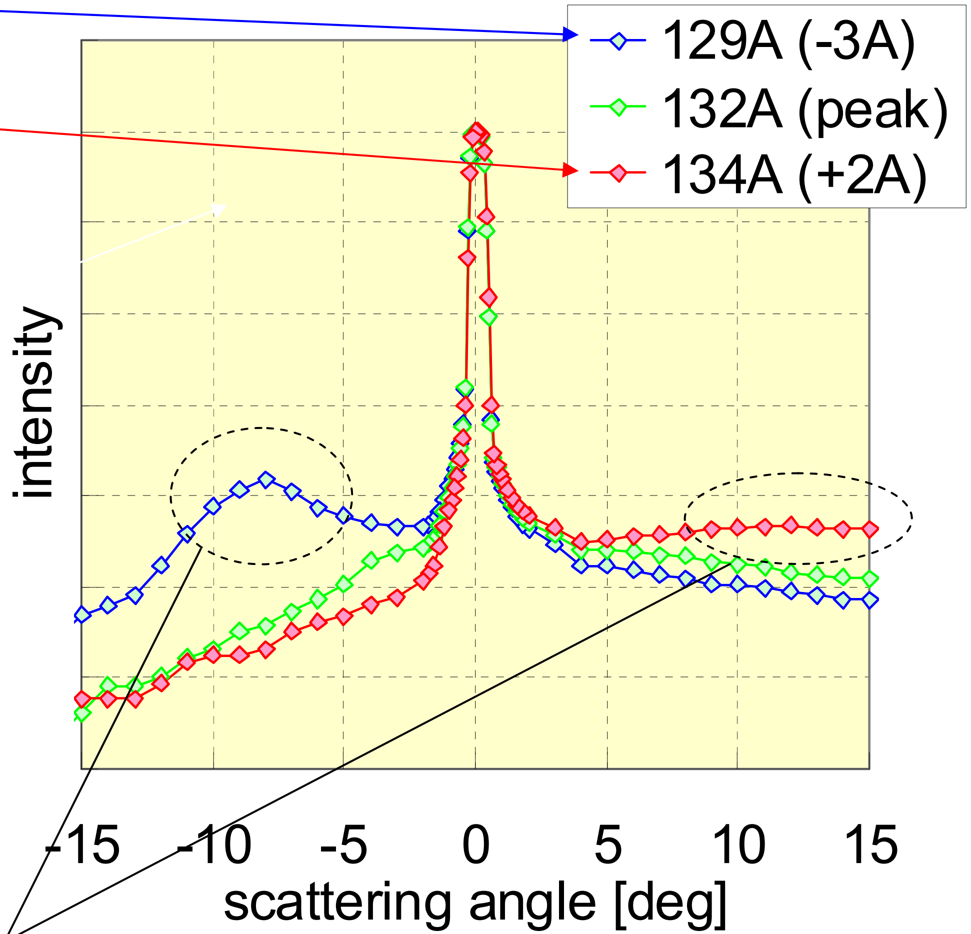


in good agreement

Scattering tail with non-peak wavelength

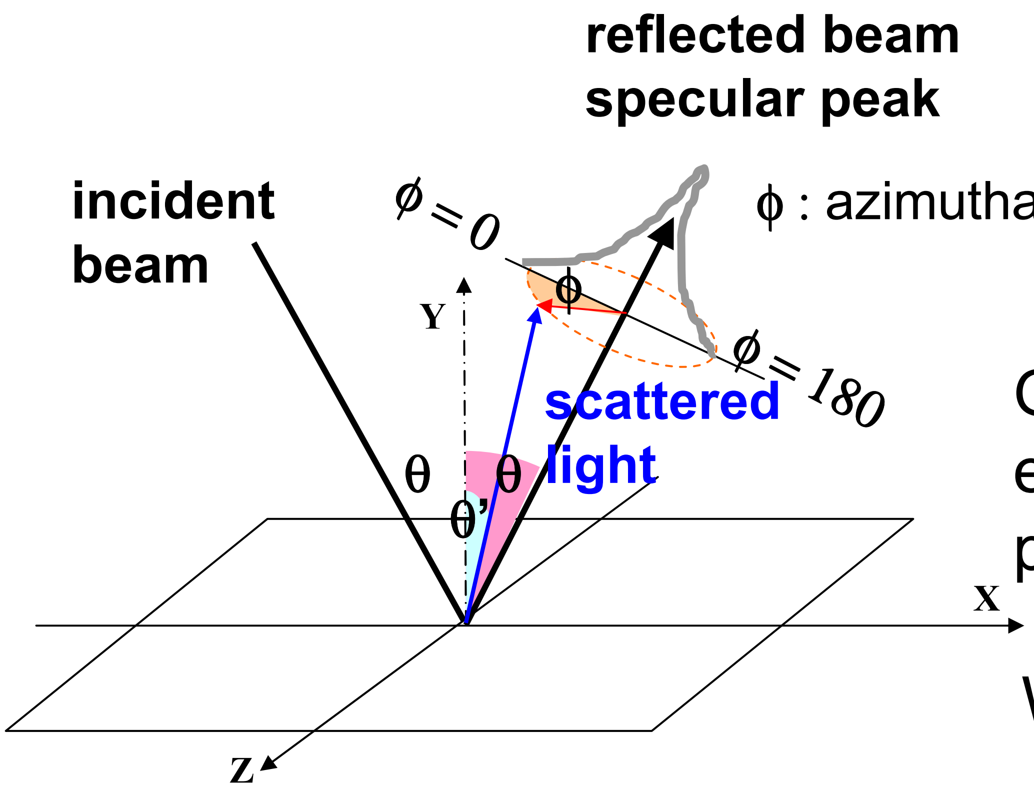
measured results





multilayer effect clearly observed

2-D distribution of scattered light



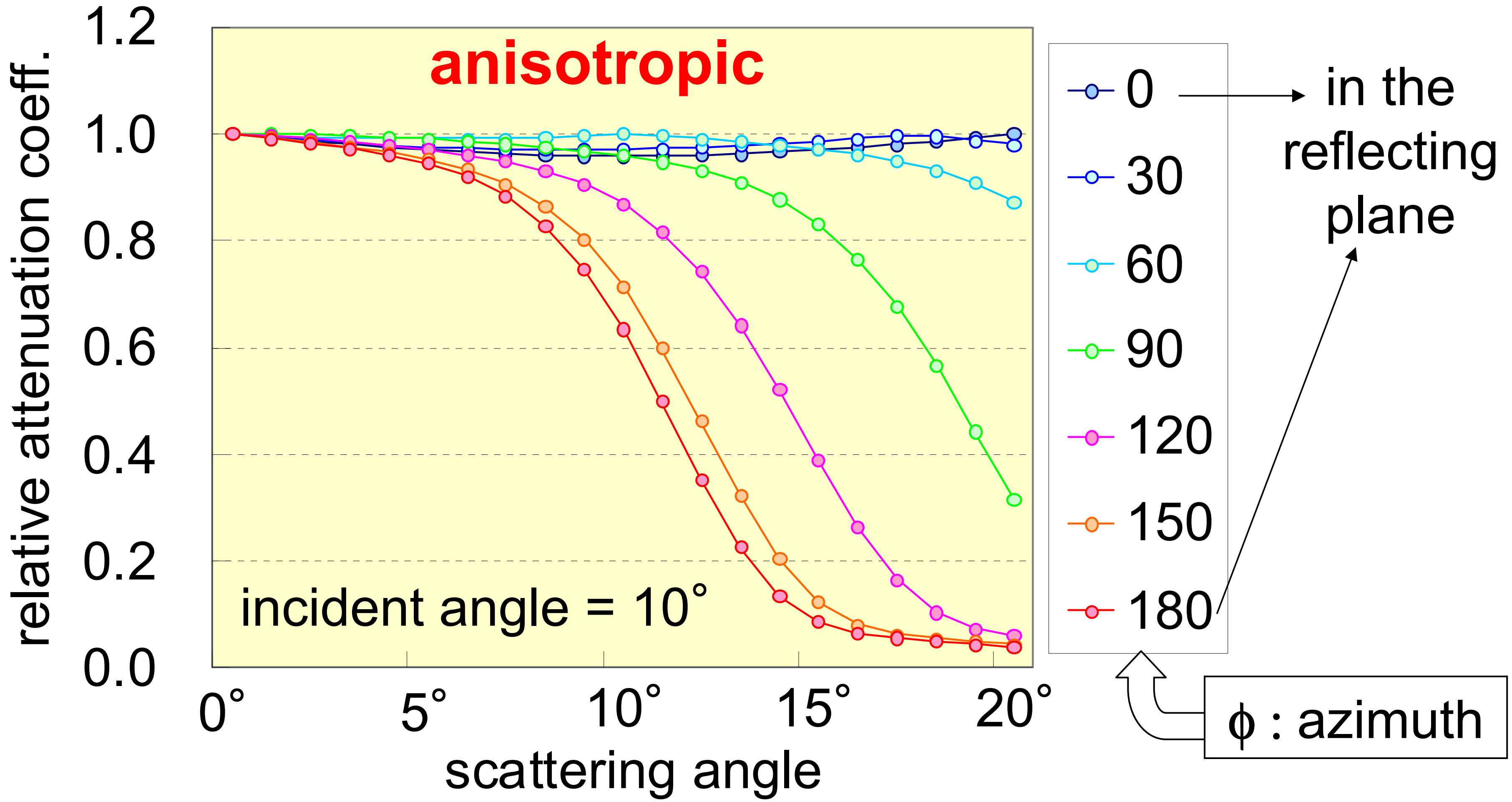
Generally, scattering tail is examined in the "reflecting plane" (X-Y plane, ϕ0 & ϕ180).

What about other directions ?

Considering optical path difference, the scattered light shows **anisotropic** distribution around the specular peak (i.e., rotational asymmetry).

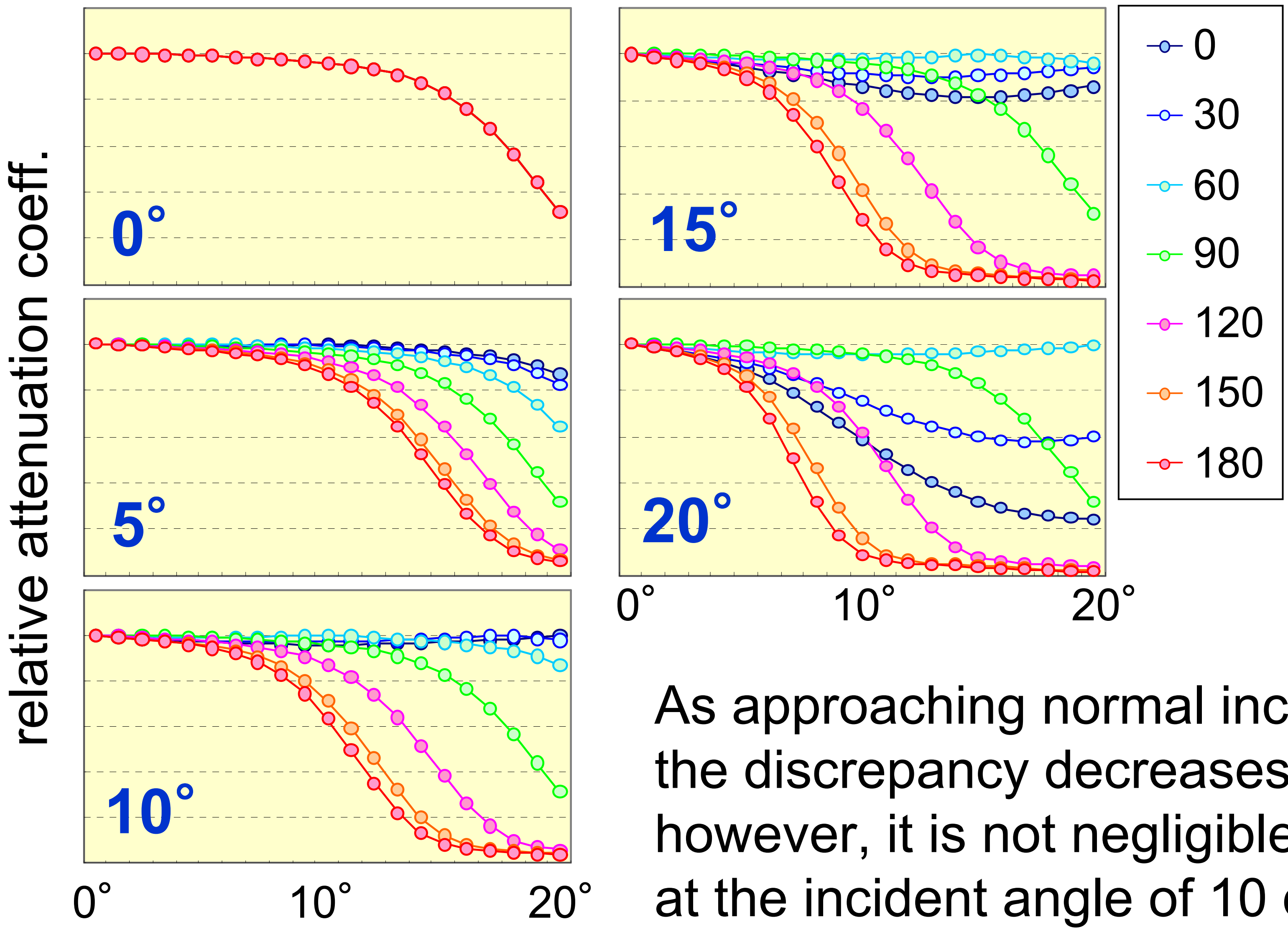
Calculated 2-D distribution

calculation: phase difference ⇒ attenuation



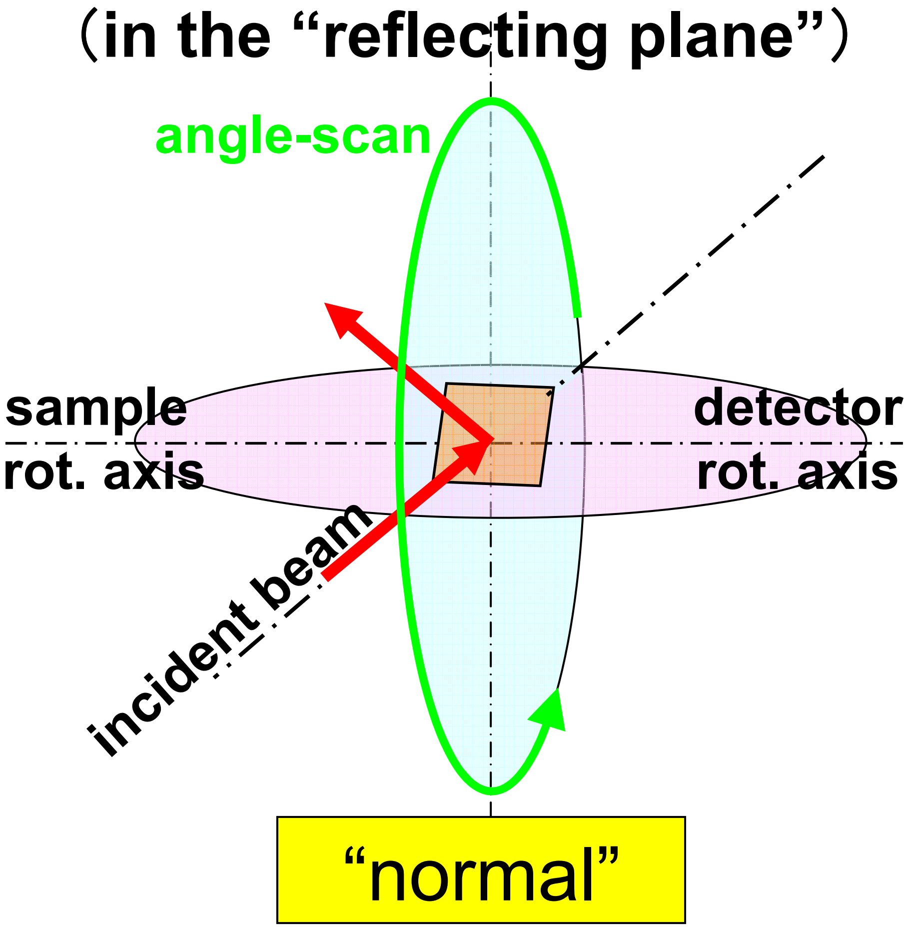
For more rigorous treatment and another approx. models…
e.g., *"D. G. Stearns et al. 1998"*, *"S.Schroeder et al. 2010"*

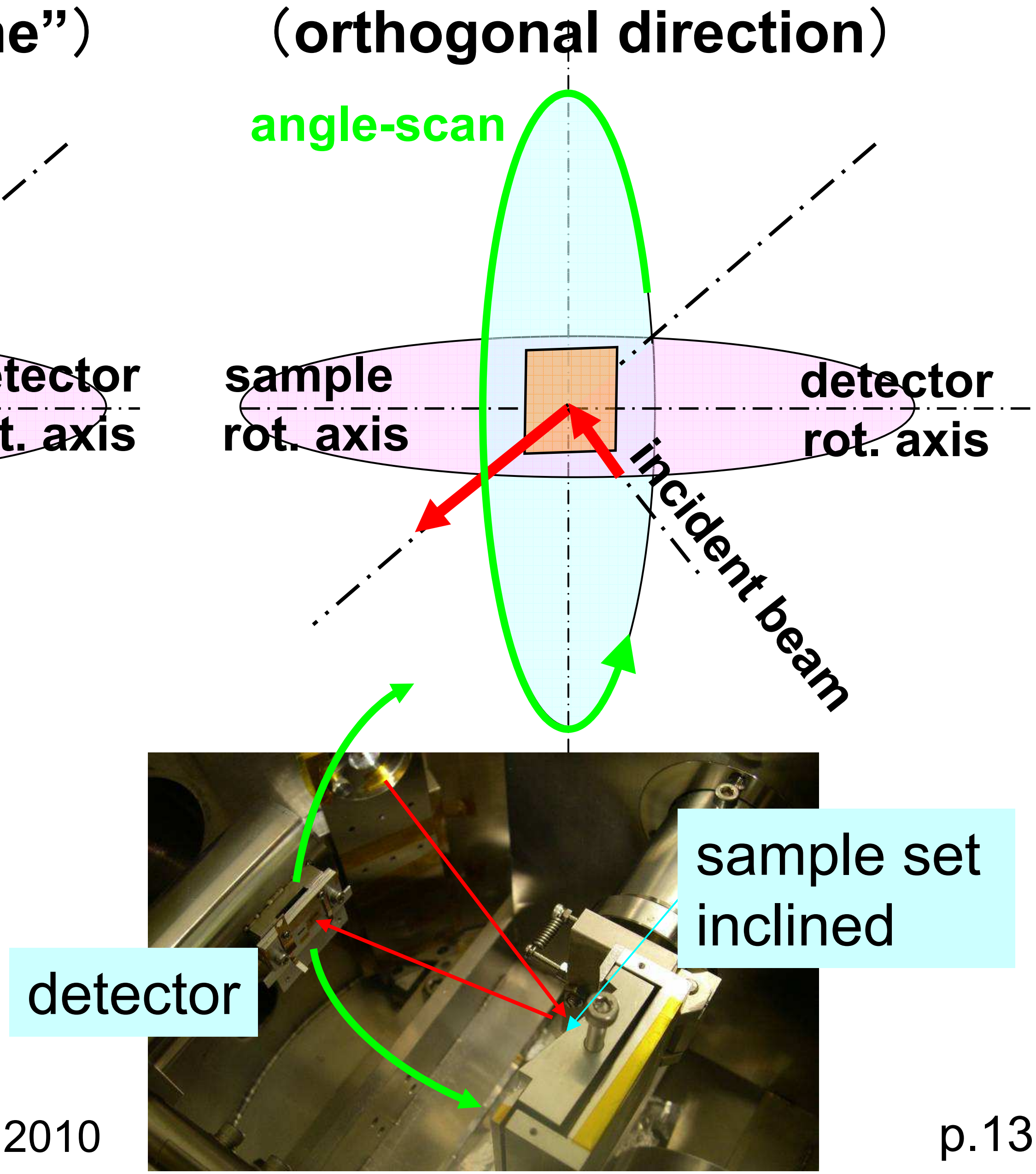
Calculation: various incident angle



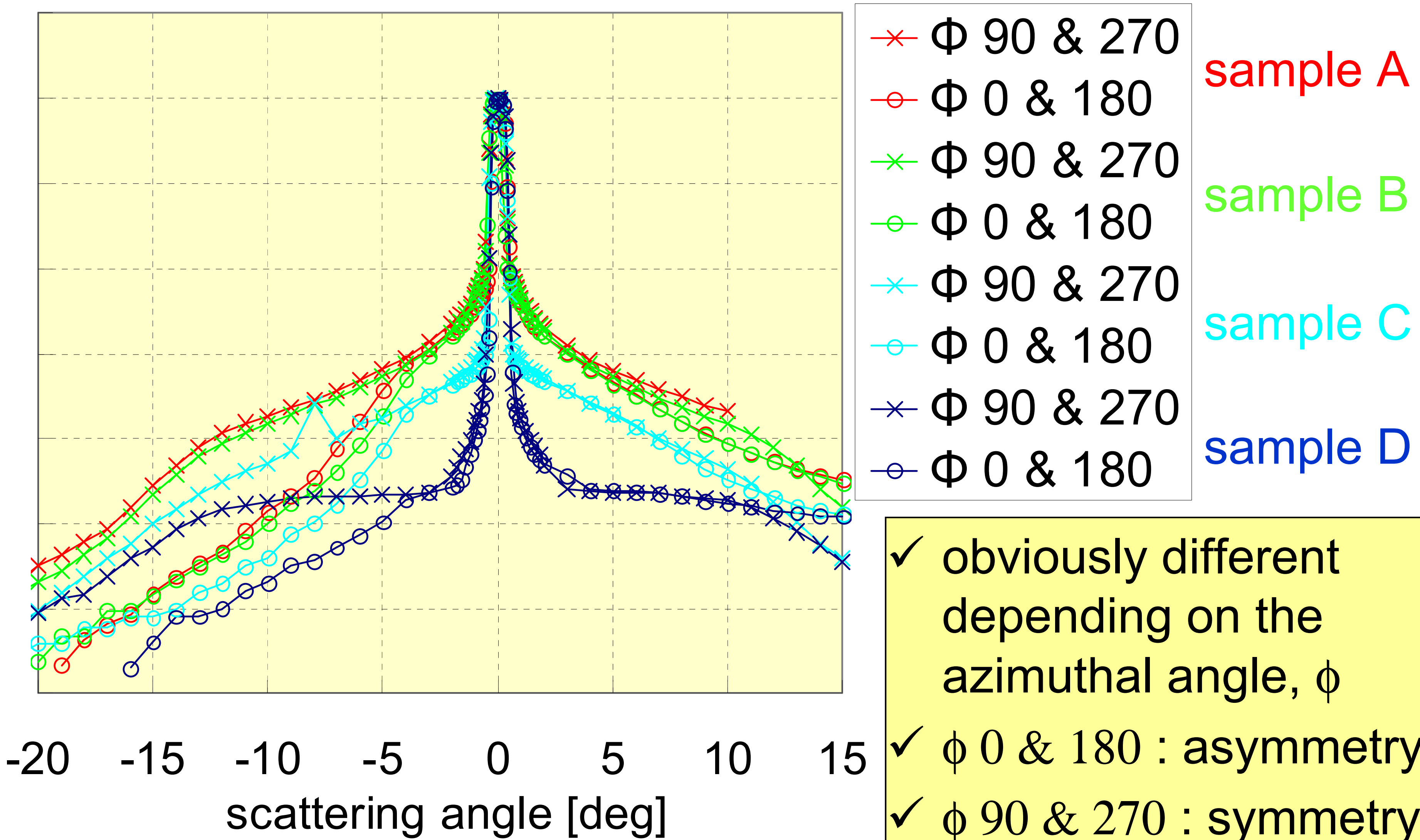
As approaching normal incidence the discrepancy decreases, however, it is not negligible even at the incident angle of 10 degree.

2-D scattering measurement configuration





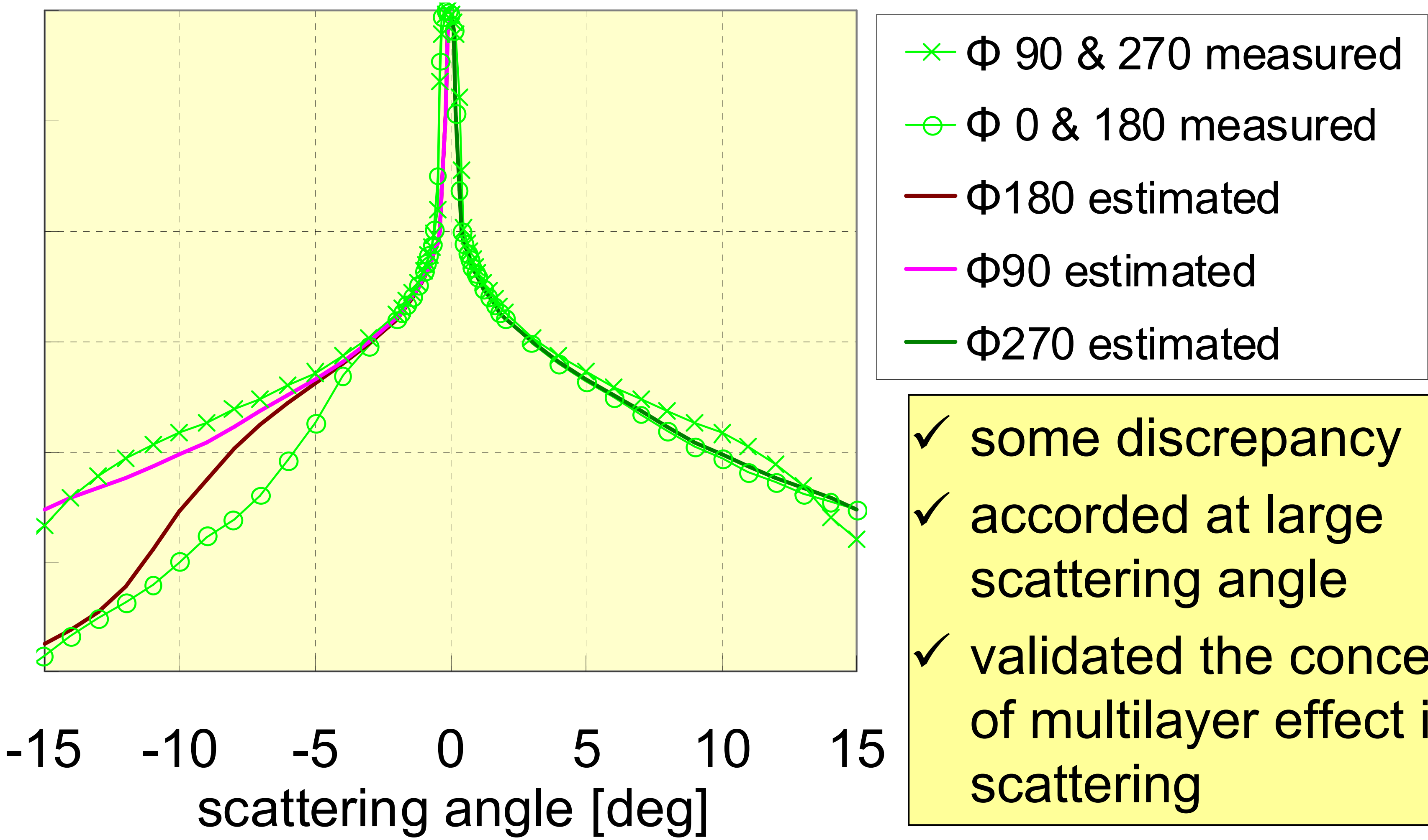
Measured 2-D distribution



- ✓ obviously different depending on the azimuthal angle, ϕ
- ✓ ϕ 0 & 180 : asymmetry
- ✓ ϕ 90 & 270 : symmetry

Comparing measurements and calculation

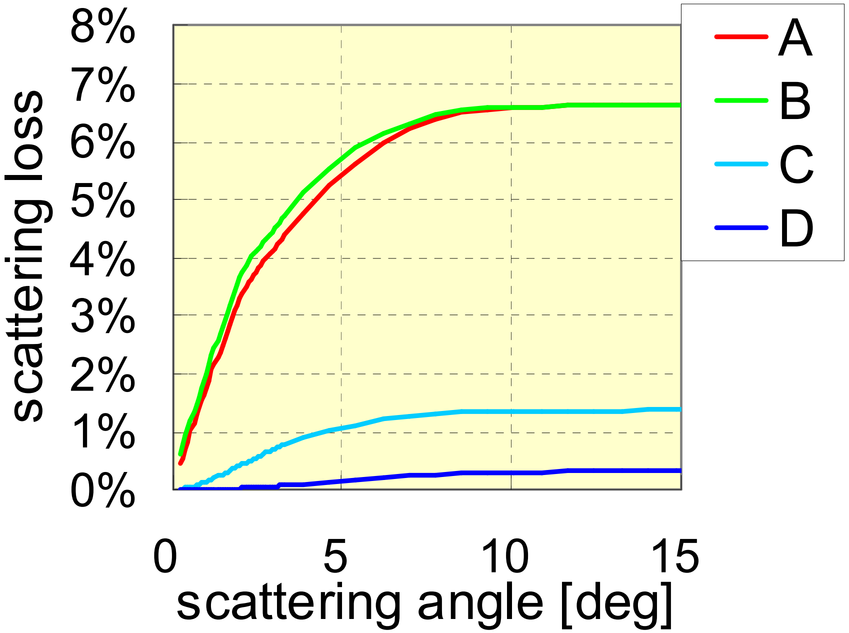
Based on “ϕ 0” profile and calculated azimuthal dependence, we estimated profiles in other directions.



- ✓ some discrepancy
- ✓ accorded at large scattering angle
- ✓ validated the concept of multilayer effect in scattering

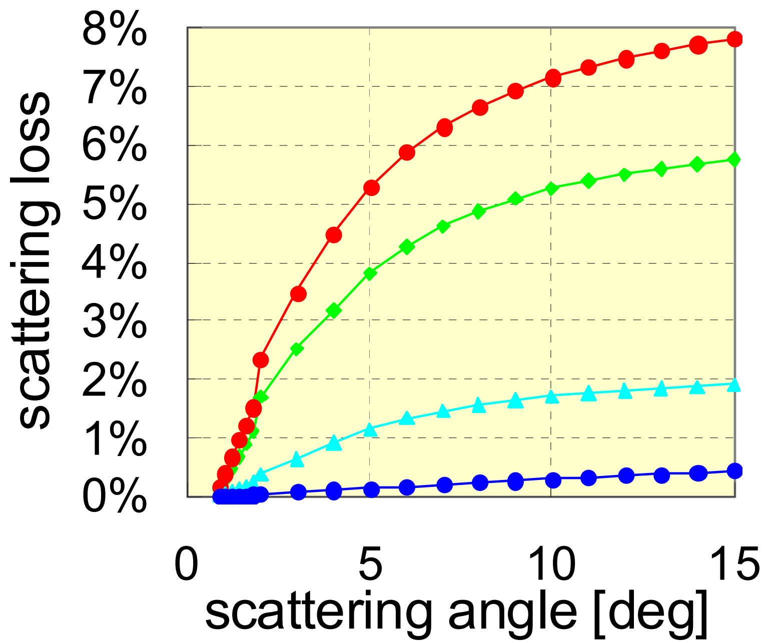
Scattering loss estimation

estimated from PSDs



sample A	:	6.6%
sample B	:	6.6%
sample C	:	1.4%
sample D	:	0.3%

deduced from measured tail

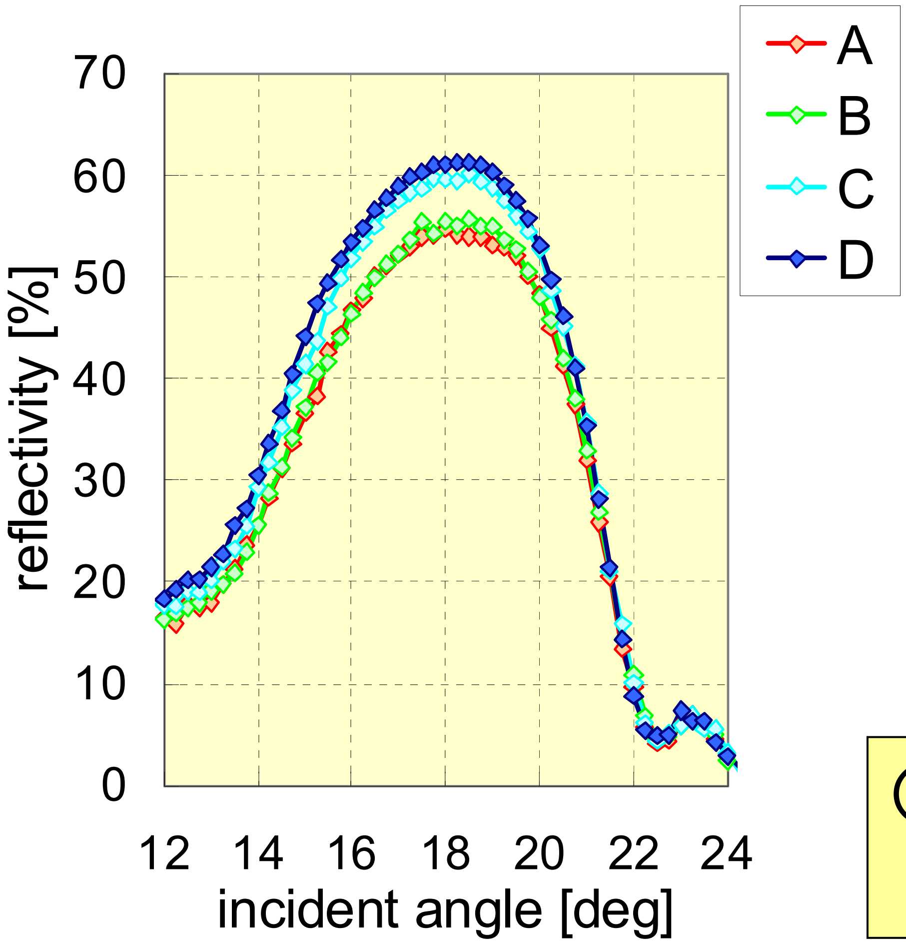


sample A	:	7.8% (~8%)
sample B	:	5.7% (~6%)
sample C	:	1.9% (~2%)
sample D	:	0.4% (~0.5%)

well-agree !

EUV reflectivity

measured EUV reflectivity



refer to “sample D”,

A Δ R = -6.5%	-6.3%	-7.4%
B Δ R = -5.6%	-6.3%	-5.3%
C Δ R = -1.0%	-1.1%	-1.5%

estimated from PSDs

deduced from scattering measurements

◎ good agreement by ~1% accuracy !

Summary

- Considering scattering from multilayer mirrors, we have to take into account the effect of interfere between each layer.
- 2-dimensional scattering distribution was experimentally examined and found to be anisotropic around the specular peak. This discrepancy is not negligible even at the incident angle of 10 degree.
- The scattering loss of EUV reflectivity can be estimated from PSD to an accuracy of a few percent.

References

- E. Gullikson, Proc. SPIE 3331, pp. 72-80 (1998)
  "Scattering from normal-incidence EUV optics"
- N. Kandaka, et al., EUVL symposium 2004 (2004)
  "Measurement of EUV scattering from Mo/SI multilayer mirrors"
- D. G. Stearns, et al., JAP 84, pp. 1003-1028 (1998)
  "Nonspecular x-ray scattering in a multilayer-coated imaging system"
- Sven Schroeder, et al., Applied Optics 49, pp. 1503-1512 (2010)
  "Angle-resolved scattering and reflectance of extreme-ultraviolet multilayer coatings: measurement and analysis"

Acknowledgements

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- staffs of KEK Photon Factory (PF) synchrotron facility
  giving us good opportunity to examine the scattering

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  preparing the samples, multilayer coatings,
  useful discussion and suggestion,
  valuable and perpetual contribution

We hope to achieve steady development of multilayer and brilliant future of EUVL project !!